

# Discovery of two new bright magnetic B stars: i Car and Atlas<sup>★</sup>

Coralie Neiner<sup>1†</sup>, Bram Buysschaert<sup>1,2</sup>, Mary E. Oksala<sup>1</sup> and Aurore Blazere<sup>1,3</sup>

<sup>1</sup>*LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France*

<sup>2</sup>*Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium*

<sup>3</sup>*Université de Toulouse, UPS-OMP, IRAP, CNRS, 14 avenue Edouard Belin, 31400 Toulouse, France*

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## ABSTRACT

The BRITE (BRiGht Target Explorer) constellation of nano-satellites performs seismology of bright stars via high precision photometry. In this context, we initiated a high resolution, high signal-to-noise, high sensitivity, spectropolarimetric survey of all stars brighter than  $V=4$ . The goal of this survey is to detect new bright magnetic stars and provide prime targets for both detailed magnetic studies and asteroseismology with BRITE. Circularly polarised spectra were acquired with Narval at TBL (France) and HarpsPol at ESO in La Silla (Chile). We discovered two new magnetic B stars: the B3V star i Car and the B8V component of the binary star Atlas. Each star was observed twice to confirm the magnetic detections and check for variability. These bright magnetic B stars are prime targets for asteroseismology and for flux-demanding techniques, such as interferometry.

**Key words:** stars: magnetic fields - stars: early-type - stars: individual: i Car, Atlas

## 1 INTRODUCTION

The BRITE (BRiGht Target Explorer) constellation of nano-satellites (Weiss et al. 2014) photometrically monitors the variations of stars with  $V \leq 4$ , with high precision and cadence, in order to perform asteroseismology. The mission consists of 3 pairs of nano-satellites, built by Austria, Canada, and Poland, carrying 3-cm aperture telescopes. One instrument per pair is equipped with a blue filter, the other with a red filter. Presently, six nano-satellites are flying, and five are observing. Each BRITE nano-satellite can observe up to  $\sim 25$  bright stars, as well as additional fainter targets with reduced precision.

Since the BRITE sample consists of the brightest stars, it is dominated by the most intrinsically luminous stars: hot stars at all evolutionary stages, and evolved cooler stars (cool giants and AGB stars). In particular, analysis of OB star variability will help to investigate outstanding issues in stellar physics, such as the sizes of their convective cores, their internal rotation profiles, and the influence of rapid rotation on their structure and evolution. Several types of pulsating hot stars are known. Pulsations in O stars are excited by the  $\kappa$  mechanism, and red noise observed in their power spectra (Blomme et al. 2011) has been interpreted as stochastically excited internal waves (Aerts & Rogers 2015). B stars also

undergo pulsations excited by the  $\kappa$  mechanism: the early types (B0-B2) are  $\beta$ Cep pulsators exhibiting mostly pressure modes (Dziembowski & Pamiatnykh 1993), while the later types (B2-B9) are Slowly Pulsating B stars (SPB) with mostly gravity modes (Dziembowski et al. 1993). Classical Be stars show  $\beta$ Cep and SPB-type  $\kappa$ -driven pulsations, but their rapid rotation also leads to the stochastic excitation of gravito-inertial waves (Neiner et al. 2012b; Mathis et al. 2014; Lee et al. 2014). Finally, the pulsations of OB supergiants are less well understood, but they seem to be driven by the  $\epsilon$  mechanism (Moravveji et al. 2012; Saio et al. 2015), and possibly stochastic excitation.

In addition to pulsations, about 10% of all hot stars are found to be magnetic (Grunhut & Neiner 2015), and the origin of their magnetic field is fossil, i.e. a descendant of the field present in the molecular cloud from which the star formed (Neiner et al. 2015a). Over the last decade, thanks to large spectropolarimetric surveys of hot stars, such as MiMeS (Wade et al. 2014, 2015), the number of known magnetic hot stars has significantly increased. Nevertheless, their number remains low, with specific types of magnetic hot targets, such as O stars, pulsating B stars, or supergiants, still relatively poorly studied. Moreover, only about ten known magnetic massive stars are brighter than  $V=4$ .

The study of the magnetic properties of pulsating hot stars is very interesting since, when combined with the study of their pulsational properties, it provides unique information about the interior of hot stars. The combination of an asteroseismic study with a spectropolarimetric study has been accomplished for only a few hot stars so far, e.g., for the  $\beta$ Cep star V2052 Oph. This star presents a magnetic field with a polar strength of about 400 G (Neiner et al. 2012a), which is above the critical field limit needed

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<sup>†</sup> E-mail: coralie.neiner@obspm.fr

to inhibit mixing inside the star as determined from theory (e.g., Zahn 2011). Asteroseismic models explaining the observed pulsational behaviour of V2052 Oph indeed required no convective core overshooting (Briquet et al. 2012), contrary to non-magnetic  $\beta$  Cep stars (e.g., Briquet et al. 2007). Moreover, in a pulsating magnetic star, the magnetic field splits the pulsation modes, modifies their amplitude, or can even inhibit certain modes by redistributing the energy into other modes. As a consequence, knowing that a field is present, its strength, and its configuration is essential to properly identify the pulsation modes and put strong constraints on seismic models. In addition, combining asteroseismology and magnetism allows us to probe the magnetic field strength and configuration inside the star, while spectropolarimetric measurements alone only probe the surface field.

Therefore, it is very useful to identify bright pulsating magnetic hot stars. In this frame, we are performing a spectropolarimetric survey of all BRITE targets, i.e.  $\sim 600$  stars with  $V \leq 4$ , with the goal of discovering new bright magnetic stars, and thus providing prime targets for BRITE asteroseismic studies. Spectropolarimetric observations of each of the  $\sim 600$  BRITE targets ( $V \leq 4$ ) are currently being gathered either from archives ( $\sim 100$  stars) or with the 3 high-resolution spectropolarimeters available in the world ( $\sim 500$  stars): Narval at the Bernard Lyot Telescope (TBL) in France, ES-PaDONs at CFHT in Hawaii, and HarpsPol on the ESO 3.6-m telescope in La Silla.

In this paper, we present the spectropolarimetric observations of two bright B stars with Narval and HarpsPol (Sect. 2), and the discovery of their magnetic field (Sect. 3). We then conclude on the great interest of these bright magnetic stars for further studies (Sect. 4).

## 2 OBSERVATIONS

The Narval spectropolarimeter covers a wavelength range from about 375 to 1050 nm, with a resolving power of  $\sim 68000$ , spread on 40 echelle orders. The HarpsPol spectropolarimeter covers a shorter wavelength range from about 380 to 690 nm on two detectors and 71 echelle orders, but with a higher resolving power of  $\sim 110000$ .

We observed our targets in circular polarisation mode. Each observation consists of 4 sub-exposures taken in a specific configuration of the polarimeter. The 4 sub-exposures are constructively combined to obtain the Stokes V spectrum in addition to the intensity (Stokes I) spectrum. The sub-exposures are also destructively combined to produce a null polarisation (N) spectrum to check for pollution by, e.g., instrumental effects, variable observing conditions, or non-magnetic physical effects such as pulsations. In addition, successive Stokes V sequences can be acquired to increase the total signal-to-noise ratio (S/N) of a magnetic measurement.

The usual bias, flat-field and ThAr calibrations were obtained each night and applied to the data. The Narval data reduction was performed using Libre-Esprit (Donati et al. 1997), a dedicated software available at TBL. The HarpsPol reduction was performed with a modified version of the REDUCE package (Piskunov & Valenti 2002; Makaganiuk et al. 2011). The Stokes I spectra were then nor-

**Table 1.** Journal of observations indicating the name of the stars, the instrument used for the spectropolarimetric measurements (H=HarpsPol, N=Narval), the Heliocentric Julian Date at the middle of the observations (mid-HJD - 2450000), the exposure time, and the mean signal-to-noise ratio of the (co-added) spectrum at  $\sim 500$  nm.

Star	Instr.	Date	mid-HJD	$T_{\text{exp}}$	S/N
i Car	H	Mar 3, 2015	7084.620	5*4*337	1272
i Car	H	Mar 9, 2015	7090.712	5*4*337	1510
Atlas	N	Nov 13, 2014	6974.600	4*245	691
Atlas	N	Nov 20, 2014	6982.515	6*4*245	3643

malized to the continuum level using IRAF<sup>1</sup>, and the same normalization was applied to the Stokes V and null spectra.

Finally, we applied the Least Squares Deconvolution (LSD) method (Donati et al. 1997) to produce a set of LSD Stokes I, Stokes V, and N profiles for each magnetic measurement. LSD requires a mask listing the lines in the spectrum, their wavelength, depth, and Landé factor. Such a line mask was produced for each star. We first extracted line lists from the VALD3 atomic database (Piskunov et al. 1995; Kupka et al. 1999) for the appropriate temperature and gravity of each star. We only used lines (including He lines) with a depth larger than 0.1. We then removed from the masks all lines that are not visible in the intensity spectra, hydrogen lines because of their Lorentzian broadening, those blended with H lines or interstellar lines, as well as lines in regions affected by absorption of telluric origin. Finally, the depth of each line in the LSD masks was adjusted as possible to fit the observed line depth.

Consecutive sequences were then co-added to produce one magnetic measurement.

### 2.1 i Car

i Car (HD 79447, HR 3663) is a B3V star with magnitude  $V=3.95$ . It was observed twice with HarpsPol on March 3 and 9, 2015. Each measurement consisted of 5 consecutive Stokes V sequences of 4 sub-exposures of 337 seconds each, i.e. a total exposure time of 6740 seconds per magnetic measurement (see Table 1). After applying LSD, the two sets of 5 sequences have been co-added to produce two magnetic measurements. For the line mask, we started from a VALD3 line list with  $T_{\text{eff}}=18000$  K and  $\log g=3.5$ , following parameters available in the literature (e.g. Zorec et al. 2009; Soubiran et al. 2010). The final mask produced for this star includes 1249 lines. The LSD profiles have a S/N of 8600 and 8100 in Stokes I, and 24600 and 31100 in Stokes V, for the two measurements respectively.

### 2.2 Atlas

Atlas (27 Tau, HD 23850) is a visual binary system with  $V=3.63$ , and a member of the Pleiades (M45) cluster. Dommanget & Nys (2000) indicated that the A component has a magnitude  $V=3.8$ , while the B companion has a magnitude  $V=6.8$ , and their separation is 0.4 arcsec. Renson & Manfroid (2009) flagged the A component as a He-weak star, and Wraight et al. (2012) provided a tenta-

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

**Table 2.** Longitudinal field ( $B_l$ ) and null (N) measurements in Gauss, with their respective error bars  $\sigma$ , significance level  $z$ , and the magnetic detection status.

Star	$B_l \pm \sigma B_l$	$z_B$	$N \pm \sigma N$	$z_N$	Detection
i Car	$-34.4 \pm 6.8$	5.1	$-1.9 \pm 6.8$	0.3	Definite
i Car	$-245.8 \pm 5.3$	46.4	$-1.3 \pm 5.3$	0.2	Definite
Atlas	$543.6 \pm 127.2$	4.3	$-9.8 \pm 127.1$	0.1	Definite
Atlas	$166.4 \pm 19.9$	8.4	$41.7 \pm 19.8$	2.1	Definite

tive variation period of 2.4624 d. The A component was also found to be a close spectroscopic binary (SB2) system Aa+Ab. Interferometry showed that the Aa and Ab components are separated by 13 mas (Pan et al. 2004) in an eccentric ( $e \sim 0.24$ ) orbit with a period of  $\sim 291$  d (Zwahlen et al. 2004). The SB2 system consists of a rapidly rotating B8III star with a B8V companion (Pan et al. 2000), with respective projected rotational velocities of about  $v \sin i = 240$  and  $60 \text{ km s}^{-1}$ .

Atlas has been observed twice with Narval on November 13 and 20, 2014. Since the diameter of the fiber of Narval is 2.8 arcsec, all 3 components of Atlas were recorded in the spectra. The first measurement consisted of 2 consecutive Stokes V sequences of  $4 \times 245$  seconds. However, the second sequence has a poor signal-to-noise ratio (S/N) and, as a consequence, only one sequence is used here. The second measurement consisted of 6 successive sequences of  $4 \times 245$  seconds in order to improve the S/N. After applying LSD, these 6 sequences have been co-added to produce one single magnetic measurement. See Table 1.

For the line mask, we started from a VALD3 line list with  $T_{\text{eff}} = 13000 \text{ K}$  and  $\log g = 3.5$ , according to the values available in the literature (e.g. Soubiran et al. 2010; David & Hillenbrand 2015). To this template mask, we added missing Ne I and N II lines extracted from VALD, which are not available in VALD3. The final mask produced for this star includes 1201 lines. The two LSD profiles have a S/N of 4673 and 12144 in Stokes I, and 15125 and 74089 in Stokes V, respectively.

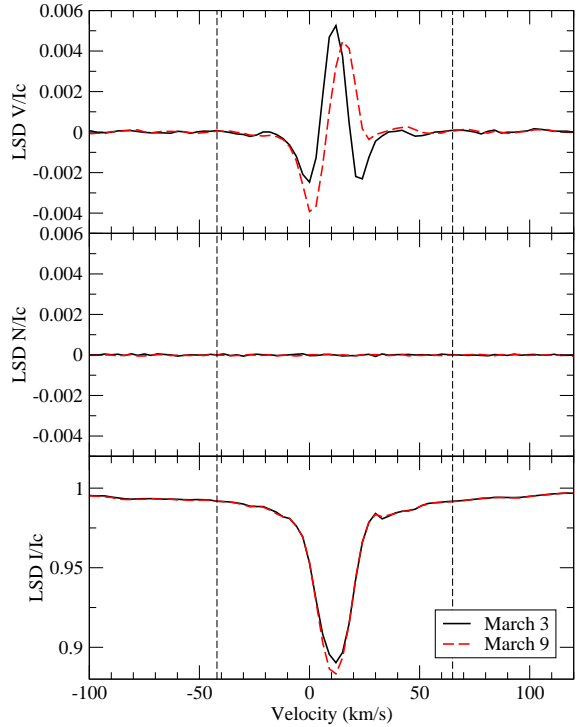
### 3 MAGNETIC ANALYSIS AND RESULTS

The detection of a magnetic field is evaluated by the False Alarm Probability (FAP) of a signature in the LSD Stokes V profile inside the LSD line, compared to the mean noise level in the LSD Stokes V profile outside the line. We adopted the convention defined by Donati et al. (1997): if  $\text{FAP} < 0.001\%$ , the magnetic detection is definite, if  $0.001\% < \text{FAP} < 0.1\%$  the detection is marginal, otherwise there is no magnetic detection.

#### 3.1 i Car

Both LSD Stokes V profiles show definite detections of a magnetic field (with 100% probability), with a Zeeman signature covering the width of the Stokes I profile, while the N profiles show no evidence of pollution of the measurements (see Fig. 1).

Using the center-of-gravity method (Rees & Semel 1979; Wade et al. 2000) with a mean wavelength of 500 nm and a mean Landé factor of  $\sim 1.46$ , we calculated the longitudinal field value corresponding to these Zeeman signatures over the velocity range  $[-42; 65] \text{ km s}^{-1}$ . The significance level  $z_B = B_l / \sigma B_l$  of the magnetic measurements is high, while the value for the N measurements ( $z_N$ )



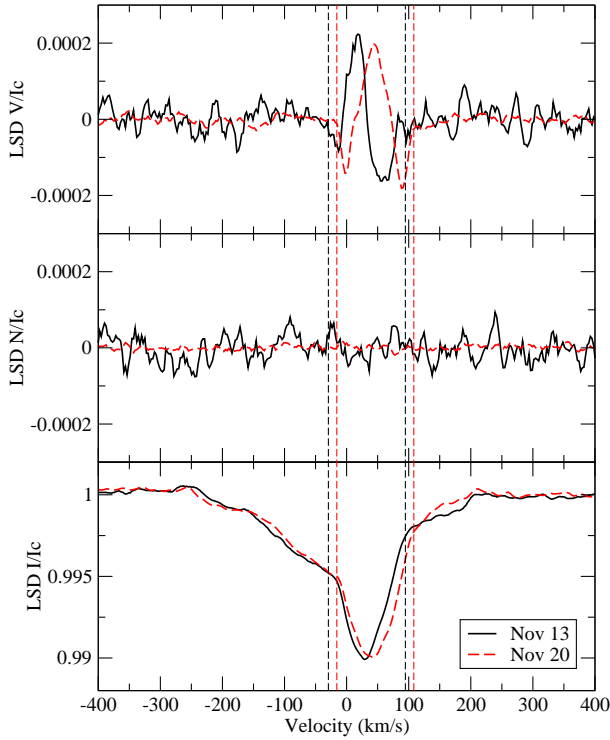
**Figure 1.** LSD Stokes V (top), N (middle) and I (bottom) profiles for the first (black solid line) and second (red dashed line) measurements of the B3V star i Car. Vertical dashed lines show the integration range for the  $B_l$  and FAP calculations.

is very low, confirming that the signature is of stellar magnetic origin. Results are shown in Table 2.

#### 3.2 Atlas

Atlas is a known multiple system, and at least two components are clearly visible in the LSD Stokes I profiles. Moreover, a slight radial velocity shift is observed between the two measurements obtained one week apart. The Zeeman signature covers the width of the Stokes I profile of the narrow-line component, which is thus the magnetic star. No magnetic signature is observed for the broad-line component. For the narrow-line component, both LSD Stokes V profiles show definite detections of a magnetic field (with 100% probability), while the N profiles show no evidence of pollution of the measurements (see Fig. 2).

To be able to extract the longitudinal field value from the LSD profiles with the center-of-gravity method, we first needed to separate the components of the multiple system. We fitted each LSD Stokes I profile with 2 gaussian components (see Fig. 3) to account for the two main components. The third weaker component of the system might be visible on the wings of the intensity profiles, but is neglected here. We then subtracted the fit of the broad component from the observed I profile, and we use the resulting LSD I profile of the narrow component only to derive the magnetic field value. This method is described in more details in Neiner et al. (2015b). The  $B_l$  values are computed with a mean wavelength of 500 nm and a mean Landé factor of  $\sim 1.5$ , over an integration range centered on the line of the magnetic component (as defined by the binary fit), i.e.  $32.6$  and  $46.2 \text{ km s}^{-1}$  for the two measurements respectively, and spanning  $\pm 62 \text{ km s}^{-1}$  (see Fig. 2). The significance level of the  $B_l$  measurements is high, while the one of the N measurements is



**Figure 2.** LSD Stokes V (top), N (middle) and I (bottom) profiles for the first (black solid line) and second (red dashed line) B8 multiple star Atlas. Vertical dashed lines show the integration range for the  $B_I$  and FAP calculations, for the first (black) and second (red) measurements.

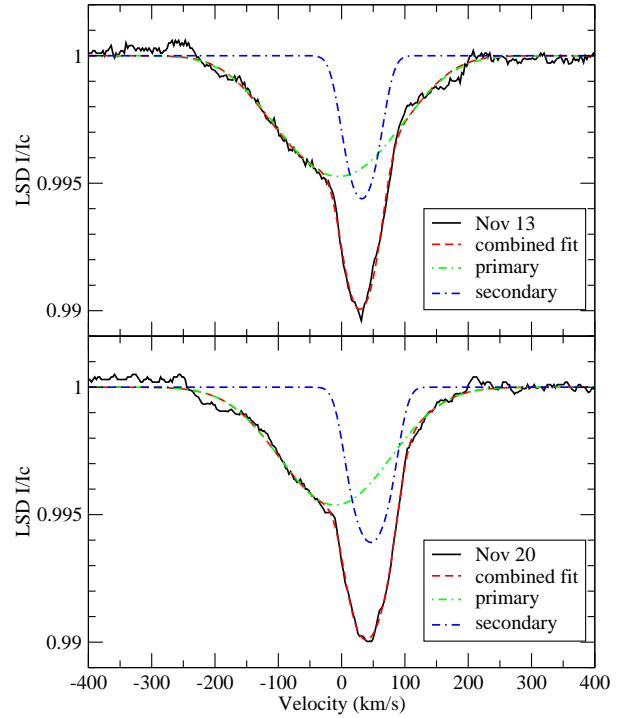
very low, which confirms that the signature is of stellar magnetic origin. Longitudinal field results are shown in Table 2.

Note that four archival spectropolarimetric measurements of Atlas exist, obtained with the Musicos spectropolarimeter, which equipped TBL before Narval was installed. In his Master thesis, [Silvester \(2007\)](#) showed that one of these four measurements exhibits a Zeeman signature as well, in spite of the 240-420 G error bars. His tentative result is thus confirmed by the much more precise Narval observations presented here.

## 4 CONCLUSIONS

In this paper, we present the discovery of two new magnetic B stars. The measured longitudinal field values indicate that their polar field strength must be of the order of 1 kG for i Car and 2 kG for Atlas. Moreover, their Zeeman signatures change from one observation to the next, which indicates that the magnetic axis is not aligned with the rotation axis. While the B8V component of Atlas shows very simple Stokes V signatures typical of a dipolar field, as observed in most magnetic hot stars ([Grunhut & Neiner 2015](#)), the very high S/N of the Stokes V profiles of the B3V star i Car allows us to see possible additional weak bumps in the wings of the line (around  $-30$  and  $50 \text{ km s}^{-1}$ ), suggestive of a more complex field. Only a handful of non-dipolar magnetic hot stars are known as of today: HD 37776, HD 32633, HD 133880, HD 137508, and  $\tau$  Sco.

The two new magnetic main-sequence B stars presented in this Letter are very bright ( $V < 4$ ), and are thus ideal for multi-technique studies. For example, they are bright enough to be observed with flux-demanding techniques, such as interferometry. In particular, they can be observed by the BRITe constellation of nano-satellites,



**Figure 3.** LSD Stokes I profiles (black solid line) of the first (top panel) and second (bottom panel) measurements of the B8III+B8V binary star Atlas, together with the combined (red dashed lines) and individual (primary in dashed-dotted green, secondary in dashed-dashed-dotted blue) fits of the two binary components.

making it possible to detect spots and probable pulsations, and to perform seismology. Combining magnetic and seismic information is the only way to probe the impact of magnetism on the physics of non-standard mixing processes inside hot stars. For example, if the strength of the magnetic field is sufficient (see e.g. [Zahn 2011](#)), it inhibits mixing inside the star and thus allows us to constrain the amount of overshooting needed in seismic models. Second, the magnetic field produces a splitting of the pulsation modes and a change of their amplitude. Knowing that a field is present, its strength, and its configuration allows us to securely identify the pulsation modes and to put strong constraints on seismic models. In addition, combining magnetic and seismic information allows us to probe the internal magnetic field, while spectropolarimetry alone only provides information about the surface field.

Furthermore, Atlas is a member of the Pleiades and, therefore, probably the brightest upper main sequence magnetic star whose age is known ( $\sim 100$  Myr, [Soderblom et al. 2009](#)). Moreover, the distance and proper motions of i Car make it a possible member of the younger Lower Centaurus-Crux group of the Sco OB2 association ( $\sim 10$  Myr, [de Geus et al. 1989](#); [de Zeeuw et al. 1999](#)). Knowing stellar ages of magnetic stars is interesting for fossil field and stellar evolution studies, and is a very strong asset for asteroseismic modelling.

However, additional spectropolarimetric observations are required to characterise the discovered magnetic fields in detail, before precise constraints can be provided for seismic models. In particular, it is necessary to determine their polar field strength, the obliquity of their magnetic axis with respect to their rotation axis, and the possible multipolar components if the field is not a pure dipole. Follow-up observations of these two targets are already



scheduled with Narval and HarpsPol, and their detailed characterization and modelling will be the purpose of a future work.

Atlas and iCar are among the very few bright ( $V < 4$ ) magnetic B stars discovered as of today. Their study will undoubtedly provide critical information about the physics inside hot stars. This will, in turn, be of great interest for other aspects of stellar physics, in particular stellar evolution, since magnetic fields influence mass-loss and angular momentum as the stars evolves.

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